

Redshift Dependent Lag-Luminosity Relation in 565 BASTE Gamma Ray Bursts

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ABSTRACT

We compared redshifts z_Y from Yonetoku relation and z_{lag} from the lag-luminosity relation for 565 BASTE GRBs and were surprised to find that the correlation is very low. Assuming that the luminosity is a function of both z_Y and the intrinsic spectral lag τ_{lag} , we found a new redshift dependent lag-luminosity relation as $L = 7.5 \times 10^{50} \text{ erg/s} (1+z)^{2.53} \tau_{lag}^{-0.282}$ with the correlation coefficient of 0.77 and the chance probability of 7.9×10^{-75} . To check the validity of this method, we examined the other luminosity indicator, Amati relation, using z_Y and the observed fluence and found the correlation coefficient of 0.92 and the chance probability of 5.2×10^{-106} . Although the spectral lag is computed from two channels of BATSE, our new lag-luminosity relation suggests that a possible lag-luminosity relation in the *Swift* era should also depend on redshift.

Key words: gamma rays: bursts — gamma rays: observation

1 INTRODUCTION

Several luminosity indicators have been proposed (Fenimore & Ramirez-Ruiz. 2000; Norris et al. 2000; Amati et al. 2002; Yonetoku et al. 2004; Ghirlanda et al. 2004.; Liang & Zhang 2005; Firmani et al. 2006; Schaefer 2007 for a review: See also Li 2007 and Butler et al. 2007 for possible evolution and bias effects). The variability-luminosity relation is the first luminosity indicator which is suggested by Fenimore & Ramirez-Ruiz (2000). It is based on the fact that the variable GRB with high variability V is brighter than the smoother one with low V . Norris et al. (2000) first recognized the spectral time lag, which is defined from two channels (25–50keV and 100–300keV) of BATSE, as a luminosity indicator based on six BATSE GRBs with the optically determined redshifts. From the BeppoSAX data, Amati et al. (2002) found the correlation between the total isotropic energy of the prompt emission and the peak energy E_p (so called Amati relation). Then Yonetoku et al. (2004) proposed E_p -luminosity relation (so called Yonetoku relation). If we use one of the luminosity indicators under the standard cosmological model, we can estimate the redshifts of GRBs whose redshifts are unknown (Schaefer et al. 2001; Yonetoku et al. 2004; Band et al. 2004).

Since these luminosity indicators such as Yonetoku relation and the lag-luminosity relation are independent each other, the redshifts derived from different indicators for the same GRB are not necessarily the same. In this Letter, we first examine the correlation of two redshifts derived from the Yonetoku relation (z_Y) and the lag-luminosity relation (z_{lag}) for 565 BATSE GRBs. In §2, surprisingly we found that the correlation between z_Y and z_{lag} is very low so that we will re-examine the lag-luminosity relation using z_Y . In §3 we found a new redshift dependent lag-luminosity relation different from the original lag-luminosity relation by Norris et al. (2000). In §4, we discuss the origin of the new lag-luminosity relation, using the subjet model (Ioka & Nakamura 2000) and the thermal model (Ryde 2004). §5 will be devoted to discussions. Throughout the paper, we assume the flat-isotropic universe with $\Omega_m = 0.30$, $\Omega_\Lambda = 0.70$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 COMPARISON OF TWO REDSHIFTS

Yonetoku et al. (2004) proposed E_p -luminosity relation and estimated the peak luminosity and the redshifts of 689 BATSE GRBs without optically determined redshifts. Recently, Tanabe et al. (2007) revised the relation using more GRBs and obtained

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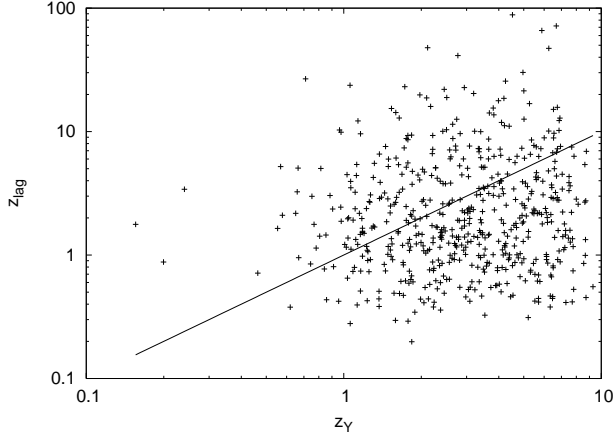


Figure 1. The distribution of (z_Y, z_{lag}) for 565 BASTE GRBs where z_Y and z_{lag} are redshifts determined by Yonetoku and the lag-luminosity relations, respectively. The correlation is very low. The solid line is $z_Y = z_{lag}$. It is expected that (z_Y, z_{lag}) distribute around the solid line.

$$\left(\frac{L}{10^{52} \text{erg s}^{-1}}\right) = 7.90 \times 10^{-5} \left[\frac{E_p^{obs}(1+z)}{1 \text{keV}}\right]^{1.82} \quad (1)$$

Although the power law index is ~ 0.2 smaller than Yonetoku et al. (2004), the relation is essentially the same so that we adopt in this Letter this revised Yonetoku relation.

Using 6 GRBs available at that time, Norris et al. (2000) found the lag-luminosity relation as

$$\frac{L}{10^{51} \text{erg s}^{-1}} = 2.18 \left[\frac{\tau_{lag}^{obs}}{0.35 \text{s}(1+z)}\right]^{-1.15} \quad (2)$$

Band et al. (2004) estimated the peak luminosity and the redshifts using the lag-luminosity relation.

In Yonetoku et al. (2004), at first 745 BATSE GRBs were sampled. 21 GRBs have $z > 12$ and 35 have no solution satisfying Yonetoku relation so that they analyzed the remaining 689 GRBs. In these 689 GRBs, 23 GRBs have $E_{iso}/L < 1 \text{s}$. In this Letter, we compare two redshifts z_Y and z_{lag} for the remaining 666 GRBs. We use lags in database for 1430 BATSE burst. We found that 621 GRBs are included in both data. 56 GRBs have negative spectral lags so that Eq.(2) can not be used for these GRBs. The number of GRBs is now 565. Figure 1 plots z_Y versus z_{lag} with the solid line being $z_Y = z_{lag}$. Surprisingly enough there are many GRBs with (1) large z_Y and small z_{lag} as well as (2) small z_Y and large z_{lag} . We see that the correlation between z_Y and z_{lag} is very low. At this point there are three possibilities; (a) the lag-luminosity relation, (b) Yonetoku relation (c) both relations are responsible for this low correlation.

We first consider the first possibility (a), since in the revised Yonetoku relation, Tanabe et al. (2007) examined the evolution effect as well as the observational selection bias and found that they are small. In Fig. 2, we plot $\log[\tau_{lag}]$ vs $\log[L_{52}]$ using z_Y where the solid line is the original lag-luminosity relation by Norris et al. (2000). The correlation coefficient is 0.38 and the chance probability is 1.7×10^{-19} which is rather large considering the number of samples 565.

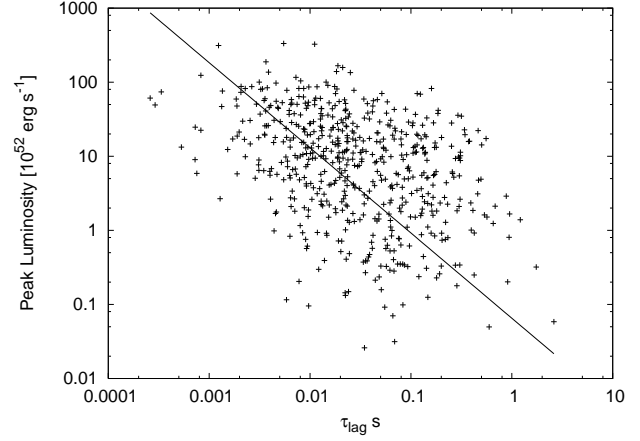


Figure 2. τ_{lag} vs L_{52} using z_Y for 565 BASTE GRBs. The correlation coefficient is 0.38. The chance probability is 1.7×10^{-19} so that the correlation coefficient is low.

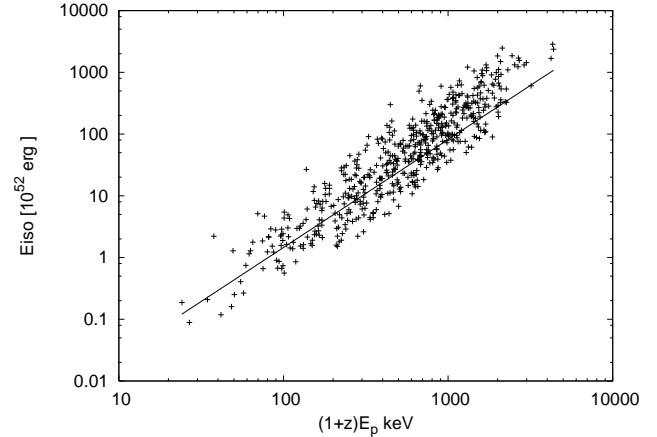


Figure 3. Amati relation in 565 BATSE GRBs. Redshifts derived from Yonetoku relation z_Y is used to estimate E_{iso} and $E_p(1+z)$. The correlation coefficient is 0.92. The chance probability is 5.2×10^{-106} so that the correlation is tight. The solid line is Amati relation (Amati 2006).

The reason for this low correlation coefficient is the large scatter around the solid line.

Then we like to ask what will happen if we adopt another distance indicator such as Amati relation. We use z_Y and plot E_{iso} and the intrinsic E_p in Fig. 3. The correlation coefficient is 0.92. The chance probability is 5.2×10^{-106} so that the correlation is tight. We can say that Amati relation is compatible with Yonetoku relation while the original lag-luminosity relation is not so. This is also the reason why we consider the first possibility (a).

3 NEW LAG-LUMINOSITY RELATION

Figure 2 shows that there is a large variance in the original lag-luminosity relation. To seek the origin of this variance we here ask the value of the redshift in Fig. 2. We divide the

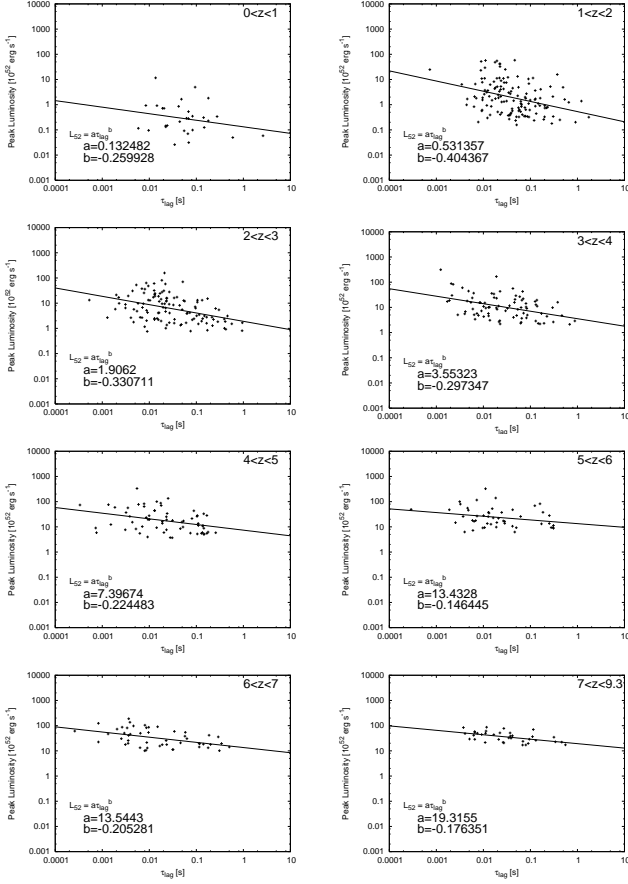


Figure 4. Lag-luminosity relations for various redshift groups as: $0 \leq z < 1$; $1 \leq z < 2$; $2 \leq z < 3$; $3 \leq z < 4$; $4 \leq z < 5$; $5 \leq z < 6$; $6 \leq z < 7$; $7 \leq z < 9.3$.devided by redshift. In each redshift group we tested the relation $L = a\tau_{\text{lag}}^b$. The best fit values of a and b are shown in each figure. The solid lines are the best-fit power-law models for each redshift group. We see that b is almost the same while a increases as a function of z .

data in Fig. 2 into redshift groups as: $0 \leq z < 1$; $1 \leq z < 2$; $2 \leq z < 3$; $3 \leq z < 4$; $4 \leq z < 5$; $5 \leq z < 6$; $6 \leq z < 7$; $7 \leq z < 9.3$. In each redshift group, assuming the lag-luminosity relation as $L = a\tau_{\text{lag}}^b$, we show in Fig. 4 the least square fit by solid lines with the value of power law index b and the amplitude a . We see that the power law indices b are almost the same while the higher redshift GRBs have larger a . This suggests the existence of the redshift dependent effect in the lag-luminosity relation. Inspired by Fig. 4, we assume that the luminosity is described by $L = A(1+z)^\alpha \tau_{\text{lag}}^\beta$, and found that the best fit curve is given by

$$\log L_{52} = -1.12 + 2.53 \log(1+z) - 0.282 \log(\tau_{\text{lag}}) \quad (3)$$

The standard deviation of the relation is $\sigma = 0.473$. In Fig. 5 we plot $\log[0.0758(1+z)^{2.53} \tau_{\text{lag}}^{-0.282}]$ versus $\log[L_{52}]$ and found that the correlation coefficient is 0.77 with the chance probability of 7.9×10^{-75} . The correlation coefficient is much higher than the original lag-luminosity relation.

In the new lag-luminosity relation, the power law index for τ_{lag} is about a factor 4 smaller than that in the original lag-luminosity relation so that one may ask for the reason of the difference. We consider the same 6 GRBs as in Norris et

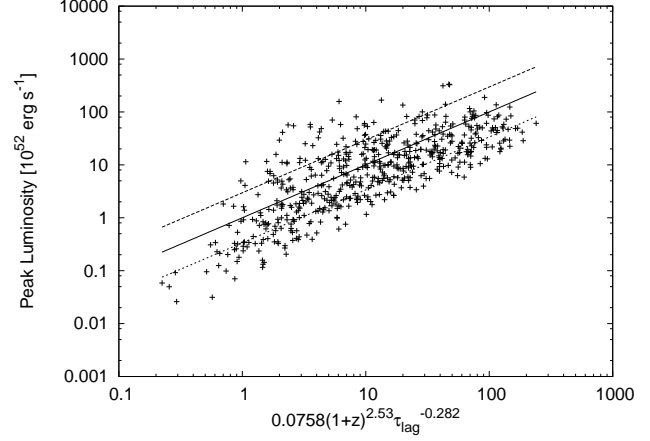


Figure 5. The new redshift dependent lag-luminosity relation in $0.0758(1+z)^{2.53} \tau_{\text{lag}}^{-0.282}$ vs L_{52} plane. The correlation coefficient is 0.77. The chance probability is 7.9×10^{-75} . The solid line is the best fitting line and two dashed lines are $1-\sigma$ (0.47 in \log_{10}) deviation line. This has a lower chance probability than the original lag-luminosity relation in Fig. 2.

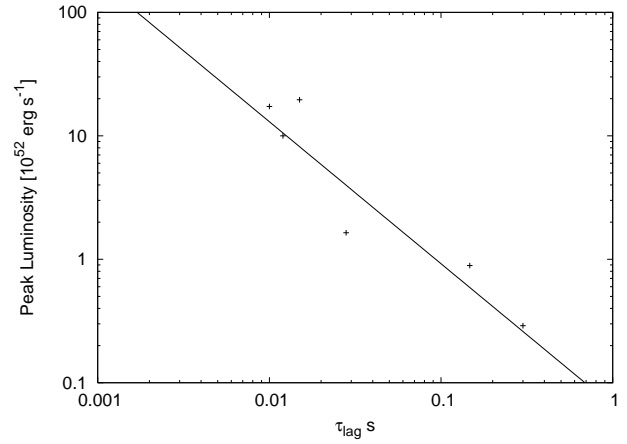


Figure 6. Lag-luminosity relation for GRBs used in Norris et al. (2000). The correlation coefficient is 0.94. The chance probability is 0.021. The solid line is Norris's original lag-luminosity relation.

al. (2000). Figure 6 shows the original lag-luminosity relation in the luminosity-spectral lag plane. We found that the correlation coefficient is 0.94, and the chance probability is 0.021. In Fig. 7 we show the new lag-luminosity relation for the same 6 GRBs in the luminosity - $0.0758(1+z)^{2.53} \tau_{\text{lag}}^{-0.282}$ plane. We found that the correlation coefficient is 0.90, and the chance probability is 0.027. As for the correlation coefficients and the chance probability, we found no significant difference between two relations in the original 6 GRBs. Therefore the new lag-luminosity relation is consistent with 6 GRBs originally used by Norris et al. (2000).

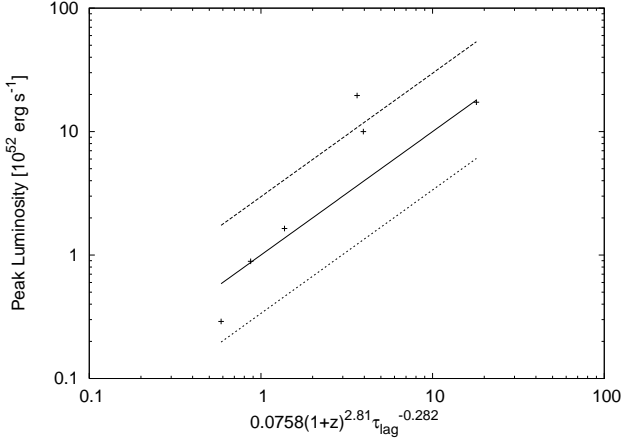


Figure 7. New lag-luminosity relation for GRBs used in Norris et al. 2000. The correlation coefficient is 0.90. The chance probability is 0.027. The solid line represents Eq. (3). Two dashed lines mark the 1- σ deviation from Eq. (3).

4 POSSIBLE INTERPRETATION OF THE NEW LAG-LUMINOSITY RELATION

Ryde (2004) studied 5 GRBs which are consistent with a thermal blackbody radiation throughout their duration and found the temperature kT can be well described by broken power law as a function of time. Figure 11 in Ryde (2004) shows the time evolution of the temperature is described as

$$kT_{obs} \approx 100\text{keV} \times t_{obs}^{-0.2}, \quad (4)$$

in the relevant early time to the spectral lag. If the peak energy of GRB is determined by the temperature of blackbody spectrum (Thompson et al. 2007; Rees & Mészáros 2005), we can identify kT_{obs} with E_p^{obs} . Assuming that E_p evolves like Eq. (4) and dt_{obs}/dE_p^{obs} is in proportion to τ_{lag}^{obs} with Yonetoku relation of $L \sim E_p^2$, we have

$$L_{52} \propto (1+z)^{1.67} \tau_{lag}^{-0.33}. \quad (5)$$

This relation has the similar value of power law index for τ_{lag} to the new lag-luminosity relation.

Ioka & Nakamura (2001) suggested the origin of the lag-luminosity relation is the viewing angle to the jet axis. They adopted the following form of the spectrum in the comoving frame, which yields a spectral shape similar to the observed Band spectrum as

$$f(\nu') = \left(\frac{\nu'}{\nu'_0}\right)^{1+\alpha_B} \left[1 + \left(\frac{\nu'}{\nu'_0}\right)^l\right]^{\frac{\beta_B - \alpha_B}{l}} \quad (6)$$

where l is a parameter which controls the smoothness of the transition between the high energy power law and the low energy one with α_B and β_B being the parameters in Band function, respectively. They adopted $l=2$ in their application to the original lag-luminosity relation. For general l , we can derive the following equation

$$L = \nu F_\nu \propto \nu^3 \delta T_p^{\frac{-1+\alpha_B}{l}} \quad (7)$$

where δT_p is the spectral lag, and ν is the intrinsic frequency. Since ν is related to ν_{obs} fixed by BATSE energy channels as $\nu = (1+z)\nu_{obs}$, we can rewrite Eq. (7) as

$$L \propto (1+z)^3 \tau_{lag}^{-0.3} \quad (8)$$

for $l = 6$. This is qualitatively consistent with the relation in Eq. (3).

5 DISCUSSIONS

The definition of the spectral lag depends on the redshift from the beginning. The spectral lag is calculated from the data of the observed two channels in 25-50 keV and 100-300 keV. However in GRB rest frame for $z = 4$, for example, two channels are 125-250 keV and 500-1500 keV. Therefore the lower channel for $z = 4$ corresponds to the higher channel for $z = 0$. If the spectral lag depends on the observed photon energy even for $z = 0$, the lag-luminosity relation should depend on redshifts for $z \neq 0$ so that our redshift dependent new lag-luminosity relation is not so strange. If the lag-luminosity relation does not depend on the redshift, the spectral lag should not depend on the intrinsic photon energy. However the concept of the spectral lag comes from the fact that the peak time depends on the photon energy. In reality, Norris et al. (2000) showed that the lag between channels 4(> 300keV) and 1(25-50keV) is $\sim 2 \sim 3$ times larger than that between channels 3(100-300keV) and 1.

We derived the new lag-luminosity relation from 565 GRBs while Norris's original relation was derived from 6 GRBs. In this Letter, the only assumption used to derive the new lag-luminosity relation is that Yonetoku relation is free from serious evolution and selection bias effects. The new lag-luminosity relation has lower chance probability than the original lag-luminosity relation by Norris et al. (2000) and is compatible with 6 GRBs used in Norris et al. (2000).

Finally we discuss redshifts determined by the new lag-luminosity relation. Equation (3) can be rewritten as

$$\frac{d_{L,26}^2}{(1+z)^{2.81}} = 0.0758 \frac{(\tau_{lag}^{obs})^{-0.282}}{4\pi F} \quad (9)$$

for each GRB, where $d_L[\text{cm}]$ is the luminosity distance and $F[\text{erg cm}^{-2} \text{s}^{-1}]$ is the photon energy flux. The left hand side of Eq. (9) as a function of z begins from zero, has a maximum at $z \sim 4$ and then decreases. The new lag-luminosity relation has one- σ deviation of 0.47 in log10. Then the right hand side of Eq. (9) changes a factor 3 so that the accuracy of redshifts is not so good. It often occurs that there is no solution for z like in Amati relation.

We need tighter lag-luminosity relation to estimate redshifts. The spectral lag for BATSE GRBs is defined from two channels in BATSE. However *Swift* does not have such two channels so that a new definition of a spectral lag is needed in the *Swift* era. Then we may construct the tighter lag-luminosity relation in the *Swift* era using *Swift* GRBs with known redshifts. Our results suggest that such a lag-luminosity relation in the *Swift* era should depend on the redshift.

So far *Swift* observed ~ 200 GRBs but only ~ 50 GRBs have spectroscopically determined redshifts. For these *Swift* GRBs without redshifts, if we can determine redshifts only from gamma ray observations, redshifts might be estimated in advance of deep follow-ups so that possible high redshift GRBs might be selected for detailed observations. Therefore it is urgent to find the lag-luminosity relation ,@which does not need E_p , in the *Swift* era.

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